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Vision Research 43 (2003) 1211–1222

Vision Research

www.elsevier.com/locate/visres

Can the magnocellular pathway read? Evidence from studies of color

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Received 4 June 2002; received in revised form 27 August 2002

Abstract

A review of the neurophysiological literature suggests that the magnocellular pathway has adequate spatial-frequency and contrast sensitivity to perceive text under normal contrast conditions (>10%) and also is suppressed by red light. Results from three experiments involving color and reading show that red light impairs reading performance under normal luminance contrast conditions. However in a fourth experiment, isoluminant color text, designed to selectively activate the parvocellular pathway, is easier to read under red light. These discrepant results suggest that the magnocellular pathway is the dominant visual pathway for text perception. Implications for reading models and developmental dyslexia are discussed.

Keywords: Reading; Word recognition; Dyslexia

1. Introduction

Livingstone and her colleagues (Livingstone, Rosen, Drislane, & Galaburda, 1991) were the first to report abnormalities in the magnocellular (M) layer of the lateral geniculate nucleus (LGN) of dyslexics. Many studies have subsequently reported M processing deficits, through the study of flicker fusion thresholds (Chase & Jenner, 1993), motion judgment tasks (Demb, Boynton, Best, & Heeger, 1998; Demb, Boynton, & Heeger, 1998; Eden et al., 1996; Slaghuis & Ryan, 1999; Talcott, Hansen, Assoku, & Stein, 2000), evoked potential measures (Romani et al., 2001) and the spatial-frequency (SF) doubling illusion (Pammer & Wheatley, 2001). Together, these studies suggest dyslexic M impairments can be found throughout the visual system, from the retina up to and including cortical area MT.

Many reading researchers, however, have treated these results cautiously because other studies have not found dyslexic M impairments (see Skottun, 2000 for a review of the psychophysical literature; Johannes, Kussmaul, Muente, & Mangun, 1996; Victor, Conte, Burton, & Nass, 1993). Most researchers believe that developmental dyslexia is caused primarily by phonemic awareness deficits that affected a child's ability to sound out a new word (Rayner, Foorman, Perfetti, Pesetsky, & Seidenberg, 2001). From this approach, dyslexia is considered to be a linguistic dysfunction. Even if visual abnormalities do exist for a subgroup of dyslexics, such defects are considered to have little to do with their reading impairments. If the M pathway does read, however, then visual abnormalities could more important for reading than previously considered. Visual M-deficits, for example, could disrupt the orthographic processing of text, interfering with letter identification and indirectly hampering phonological analysis.

Several visual M deficit models of developmental dyslexia have been proposed (Chase, 1996; Cornelissen et al., 1998; Stein & Walsh, 1997). Skottun and colleagues (1999, 2000) challenged this work in a review of vision lesion and human psychophysical studies. They determined that M neurons were unlikely to be involved in the processing of text and concluded a magnocellular deficit does not cause reading problems. In this paper, we draw a different conclusion from a review of the some of same literature and suggest that the M pathway not only

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0042-6989/03/$ - see front matter
doi:10.1016/S0042-6989(03)00085-3

processes text but also may be the primary pathway for text perception at normal contrast levels. In support, we present evidence from four experiments that show chromatic filters that selectively suppress M function, but not parvocellular (P) neurons, impair reading performance in normal adults. We begin with background review.

1.1. Magno- and parvocellular pathways in vision

In the primate visual system, approximately 85% of cortical projections are conducted through two parallel pathways (Dacey, 2000; Lee, 1996; Livingstone & Hubel, 1987). The two channels are most clearly distinguished in the LGN of the thalamus, where cell-body stains show six layers of cells organized into four bands of small cells (parvo) and two bands of large cells (magno). Although the two pathways are not considered to be functionally independent subsystems (Merigan & Maunsell, 1993), many studies (for reviews, see Lee, 1996 or Shapley, 1990), have shown these two pathways to be sensitive to different visual spatial and temporal characteristics. The primate P channel responds to color opponency (Merigan, 1989), transmits information more slowly (Schiller & Malpeli, 1978), and for achromatic stimuli reaches threshold at about 10% contrast. The M neurons increase their response to changes in contrast (contrast gain) more rapidly than neurons in the P pathway and have contrast thresholds that are below 2% (Purpura, Kaplan, & Shapley, 1988). M-cell signals reach the visual cortex 7–10 ms faster than P-cells (Maunsell & Gibson, 1992). In addition, when LGN cells from the magnocellular layer are destroyed, macaque vision is less sensitive to low SF displays that flicker rapidly, especially at rates at and above 10 Hz (Merigan & Maunsell, 1993), suggesting the M channel plays a key role in motion detection and tracking a moving object.

1.2. Spatial resolution

To determine if the magnocellular pathway can process text, the critical issue concerns the SF sensitivity of the M and P pathways. First, we will estimate the bandwidth sensitivity of the M and P systems under normal contrast and luminance conditions. Then we will examine what SFs are used for reading.

The P pathway originates from midget ganglion cells in the retina, whereas the M pathway originates from parasol ganglion cells. In the fovea, a midget ganglion cell can receive input from a single cone (Wassle & Boycott, 1991), providing spatial resolution as high as 60 cycles/deg. Parasol ganglion cells in the fovea can respond up to about 20–40 cycles/deg (Crook, Lange-Malecki, Lee, & Valberg, 1988). Yet, studies of the spatial resolution of individual P- and M-cells as a function of eccentricity show considerable overlap, whether measured from the LGN (Blakemore & Vital-Durand, 1986; Derrington & Lennie, 1984) or from the retina (Crook et al., 1988). Physiological measures of acuity are affected by a number of factors other than anatomy, including eye movement, optical degradation, and sampling density (Lee, 1996). For example, there is no reduction in spatial resolution when P-ganglion cells are activated by a single cone. However, ganglion cells with larger receptive fields receive converging input from many contiguous interneurons. Since spatial summation in M- and P-cells is linear (Kaplan, Lee, & Shapley, 1990), the larger summation area reduces resolution.

1.2.1. Maximum SF sensitivity

Merigan and Katz (1990) found that macaque visual acuity, like humans, peaks at about 38 cycles/deg at the fovea, considerably below the peak threshold for single P-ganglion cells. Based on a two-dimensional Nyquist sampling distribution model, their results were closely correlated to cone density near the fovea (within 10 deg) and to P-ganglion cell distribution beyond 10 deg. M-ganglion cells are less densely distributed with approximately one M-cell for every eight P-cells (Silveira & Perry, 1991), so by this model, the M pathway acuity was estimated to be about three to four times less than the P pathway. In a follow-up study, destruction of the P pathway reduced foveal acuity four-fold to a peak sensitivity of 10 cycles/deg (Lynch, Silveira, Perry, & Merigan, 1992). Since visual acuity threshold is dependent upon the more densely distributed P-cells, the maximum SF sensitivity of the P channel within the fovea (3 deg radius) can be determined to be about 25–40 cycles/deg, and the peak SF sensitivity of the M channel is about a fourth less, or 6–10 cycles/deg. Lee (1996) suggested that visual acuity thresholds may be higher for one-dimension visual displays, such as sine-wave gratings, or for targets that are unlikely to suffer from Nyquist limitations.

1.2.2. Minimum SF sensitivity

The minimum SF sensitivity of the two pathways can be estimated from other measures conducted in lesion studies (Lynch et al., 1992; Merigan, 1989; Schiller & Logothetis, 1990). In their review of this research, Merigan and Maunsell (1993) reported that M pathway lesions did not affect luminance contrast sensitivity with stimuli presented at low temporal frequencies, suggesting that the P pathway is sensitive to SFs as low as 0.5 cycles/deg. Curiously, individual P-cells reach threshold at contrasts below 10% (Shapley, 1990), yet these lesion data show contrast detection as low as 0.5% for 2 cycles/deg displays. Merigan and Maunsell (1993) explained this discrepancy by hypothesizing that the sampling density distribution of P-cells improves contrast resolution through spatial and probability summation from individual cells. For displays at higher temporal fre-

quencies (e.g., above 10 Hz), M pathway lesions cause a substantial reduction in contrast sensitivity but only in the low SF range (0.5–5 cycles/deg).

The destruction of the P pathway caused a three- to four-fold reduction in contrast sensitivity for low temporal frequency displays, a result consistent with the sampling distribution model of visual acuity described above. M pathway contrast thresholds of between 10% and 50% were found for SFs up to about 8 cycles/deg, but sensitivity was much weaker for higher SFs. For a 0.7 cycles/deg grating modulated in counterphase at 10 Hz, M pathway contrast thresholds were similar to normal animals (Lynch et al., 1992). These results suggest that for low temporal frequency displays, both the M and P pathways may be sensitive to SFs as low 0.5 cycles/deg, but only the M pathway is sensitive to SFs less than 5 cycles/deg presented at a temporal frequency of 10 Hz or more.

The behavioral performance of lesioned animals is not always consistent with other physiological data on P- and M-cells, particularly with regard to visual acuity and contrast sensitivity. Factors, such as the response properties of single cells versus cell networks as discussed above, may account for some of these differences. In addition, visual stimuli may not be perceptually equivalent between a normal animal and a lesioned animal that has only one functional pathway. Visual information that is not utilized in a normal animal may become important to make a perceptual discrimination when one visual pathway is damaged. For example, Lynch et al. (1992) found that lesions of the P pathway in the LGN did not impair vernier acuity, contrast sensitivity under certain conditions, or form discrimination (although Schiller & Logothetis, 1990 reported both form and text perception to be severely compromised with a P pathway lesion). With these limitations and discrepancies in mind, estimates of the SF sensitivity of the two pathways can be made from this literature review.

1.2.3. SF sensitivity of M and P pathways

Under normal visual conditions, human observers show a preferred sensitivity bandwidth for each pathway with a cross-over point at about 1.5 cycles/deg (see Skottun, 2000 for a review). The M pathway has been found to be more sensitive to SFs below 1.5 cycles/deg, whereas the P pathway is differentially sensitive to SFs above 1.5 cycles/deg. However, there is considerable SF overlap between the two pathways in the low- to mid-SF range. For SFs above 10 cycles/deg or for displays with high temporal frequencies, one pathway may be more efficient than the other, particularly when measuring contrast sensitivity thresholds, but both pathways seem capable of processing SFs below 10 cycles/deg that are presented at low temporal frequencies and under normal contrast conditions (>10%).

1.3. Role of magnocellular pathway in reading

There is considerable disagreement about the role of the M channel in text processing (Skottun, 1997; Skottun, 2000; Stein & Walsh, 1997). Breitmeyer (1980) proposed a reading model in which the M or transient channel has an indirect role in text recognition. In his model, text is only processed in the P or sustained channel. Because the duration of P channel response can outlast the saccade fixation, the function of the M channel is to inhibit activity in the P channel, suppressing any visible persistence and avoiding blurring that would occur from the overlap of images in the summation of two saccades. Several cognitive (Chase, 1996) and physiological (Skottun, 2000) criticisms of this model have been made, including the fact that it is the M channel and not the P channel that is suppressed during a saccade (see Breitmeyer & Ogmen, 2000 or Skottun & Parke, 1999 for a review).

Can the M pathway directly process text? In a recent study that examined a variety of font styles and sizes, Majaj, Pelli, Kurshan, and Palomares (2002) reported the SF channels used for reading varied with the stroke frequency of the text by the formula: channel frequency/10 cycles/deg = (stroke frequency/10 cycles/deg)$^{2/3}$. Stroke frequency provided a measure for the SF of the font. Using a horizontal line drawn through the middle of each letter of the alphabet, a count was made for how many times this line was crossed by the features of a letter. The stroke frequency (strokes/deg) for a font was calculated as the average count per letter divided by the average letter width. They found that channel frequencies used for reading ranged from 0.1 to 10 cycles/deg. Legge, Pelli, Rubin, and Schleske (1985) reported that the optimal bandwidth for text processing was two cycles per character and that the optimal character size was between 0.2 and 3.0 deg/character. Together these findings suggest that the optimal SF for text processing is between 1 and 6 cycles/deg, although the visual system is capable of processing text with SFs below and above this range.

Based on the review of the anatomical and physiological data described above, the SF channels used for text processing are well within the sensitivity range of the M pathway. As long as high contrast displays (>10%) are used, the M pathway should have no difficulty processing text. Because visual saccades during reading rarely exceed 4 Hz, the P pathway also would be active in text processing.

Chase (1996) has proposed a reading model in which the M channel directly encodes text. Visual perception is not instantaneous but rather results from the integration of information as it is processed through the P and M channels at different rates. Legge (1978) showed the low SFs (0.375–1.5 cycles/deg), that define the global pattern or shape, are extracted rapidly in 60–80 ms. Higher SFs

(6.0–12.0 cycles/deg) are processed more slowly, requiring 150–200 ms. In the early stages of visual processing, perception is diffuse, primarily made up of low SF information provided by the M channel. In the later stages, higher SFs are added by the P channel, providing finer details. Perceptual identification begins immediately with the first available information (e.g. low SFs), integrating the higher frequency information within the context of mental representations already formed (Eriksen & Schultz, 1979; McClelland, 1979). Thus, the processing speed efficiency depends upon the acuity requirements of the task. Global shape discrimination can be made more rapidly (Badcock, Whitworth, Badcock, & Lovegrove, 1990; Navon, 1977), based on an analysis of low SF information carried in the faster M pathway (Hughes, Nozawa, & Kitterle, 1996), whereas perception of more localized details requires better acuity and the high SF information provided by the slower P pathway.

In the Chase model, the M channel provides a low SF visual prime that can be used for orthographic identification. If sufficient information is available, words are identified rapidly on the basis of the M channel alone. However, when the orthographic system cannot make an identification, the system must await for further detailed input from the P channel.

1.4. Color and text processing

If the M pathway processes text, then reading performance will be affected by the same visual factors that change M-ganglion cell functioning. Recently, attention has turned to the use of color, specifically red light, to selectively suppress M-cell function.

1.4.1. Red light disrupts magnocellular tasks

The M channel has a specific sensitivity to longer wavelengths of light (Livingstone & Hubel, 1984). De Monasterio (1978) found that the receptive fields of type IV M-ganglion cells predominately have on-center with inhibitory-surrounds that have dominant L-cone (red) input. Reid and Shapley (1992) reported that recordings from the majority of M-cell neurons studied had a stronger L-cone input to their surround-field. Smith, Lee, Pokorny, Martin, and Valberg (1992) also found a chromatic response from the M-cell surround.

Several studies reported that diffuse red light suppressed activation of M-ganglion cells (Dreher, Fukuda, & Rodieck, 1976; Kruger, 1977; Schiller & Malpeli, 1978; Wiesel & Hubel, 1966). Additional studies have shown that red light impairs visual perception for M channel functions, such as motion, global shape, metacontrast, and flicker perception.

Breitmeyer and his colleagues (1990,1994) completed several experiments that examined the effect of color on M channel functions. In one study (1990), the perception of both metacontrast and stroboscopic motion were decreased when stimuli were presented on a red background, although Pammer and Lovegrove (2001) found no color effect on apparent motion discrimination but did find metacontrast reduced by red light. Edwards, Hogben, Clark, and Pratt (1996) also found red light to reduce metacontrast for normal reading adults, adolescents, and reading impaired adolescents. In a second Breitmeyer study (1994), RT was slower with a red background but faster with blue only for the larger targets (>32′). Since M-ganglion cells have larger receptive fields than P-cells, the results support the idea that red light selectively disrupts M channel processing.

A recent study supported this conclusion using the global precedent effect (Navon, 1977). Michimata, Okubo, and Mugishima (1999) found the perception of a global visual pattern is disrupted when presented on a red background. Since global processing is dependent upon the lower SF of the pattern (Hughes et al., 1996), and the M channel is more responsive to low SFs, these results suggest that red light impairs M channel function.

A number of studies have shown visual sensitivity reduction to flickering light under red background conditions (Eisner & MacLeod, 1981; Stromeyer, Chaparro, Tolias, & Kronauer, 1997; Stromeyer, Cole, & Kronauer, 1987; Swanson, Pokorny, & Smith, 1988). Recording ganglion cell activity from the retina of macaques, Pokorny, Smith, Lee, and Yeh (1999) concluded that changes in flicker sensitivity were caused by suppression of M-cell responses due to L-cone input.

1.4.2. Color and reading

Since the M pathway is suppressed by red light, reading performance with longer wavelengths also should be impaired compared with light that is shorter in the visible spectrum. Several studies have examined the effects of color on reading. In general, reading performance tends to be better with blue filters for both normal and disabled readers (Iovino, Fletcher, Breitmeyer, & Foorman, 1998; Solan, 1998; Solan, Brannan, & Ficarra, 1997; Solman & Cho, 1991; Williams, LeCluyse, & Rock-Faucheux, 1992), but red light also has been reported to slightly impair reading performance (Legge & Rubin, 1986).

This literature, however, has many methodological problems. Many of the studies (e.g., Williams et al., 1992) have used colored transparencies that lack bandwidth specificity and act more as a broad-band filter. Only one of these studies (Solman & Cho, 1991) reported the cone transmittance characteristics of their filters. In addition, some of the studies (e.g., Iovino et al., 1998) did not control for luminance and only a few controlled for contrast when comparing different color conditions. Since changes in luminance and contrast affect text perception and metacontrast functions (Pammer & Lovegrove, 2001) some of the results

showing improved performance under blue light may be due to weaker contrast and not shorter wavelength. Other studies (e.g., Legge & Rubin, 1986) used reading measures that may have been insensitive to small changes in performance.

Finally, none of these studies has determined whether reading actually benefits from more blue light or less red light. Reading performance with a blue filter could improve because longer wavelengths (red) are absent, not because blue is better. In fact, blue filters transmit wavelengths that mostly activate S-cones, which comprise only about 5%–10% of the all the cones (Dacey, 2000), and therefore contribute little to the spectral and SF sensitivity of the eye.

For these reasons, we designed several experiments to examine the effects of color on reading. We began with a study using color transparencies.

2. Experiment 1: Irlen transparencies

2.1. Method

2.1.1. Participants

Thirty-eight college students from Mt. Holyoke College in Massachusetts volunteered to participate in the study. All reported no history of reading impairments or other learning disabilities, no color blindness, and all had normal or corrected-normal visual acuity.

2.1.2. Materials

Participants read out loud passages from the Gray Oral Reading Test (Wielder & Bryant, 1992) GORT Forms B and C, to provide measures of reading time, accuracy, and comprehension. Seven of the 13 passages were read out loud in order of difficulty (3, 5, 7, 9, 11, 12, 13), and scored for time, accuracy and comprehension following the standard GORT procedures.

Irlen transparencies (Irlen, 1991) have been proposed to improve children's reading performance. After measuring the transmittance properties of the entire set using an Agilent 8453 UV–Visible spectrophotometer, the yellow and purple transparencies were selected. Each has a complementary transmittance in their respective shorter or longer wavelength (see Fig. 1). A neutral gray density filter was added to the yellow transparency to equalize luminance. Michelson contrast was 0.51 and luminance was 28 cd/m^2 for the shorter wavelength condition (purple) and contrast was 0.60 with a luminance of 28 cd/m^2 for the longer wavelength condition (yellow). For this and the other three experiments, luminance was measured by a Minolta LS-100 meter.

2.1.3. Procedure

Participants were tape recorded while reading out loud, and reading time and accuracy were scored from the recording using the GORT error scoring procedures with the scorer blind as to the condition under which the passage was read. All seven passages from one form were read through either the yellow or purple transparency with the passages from the other form read through the other transparency. The order of the GORT forms and color by form conditions were counterbalanced throughout the experiment. Testing was conducted individually, using florescent ceiling lighting. Room luminance was 80 cd/m^2 as measured from a white paper on the reading table.

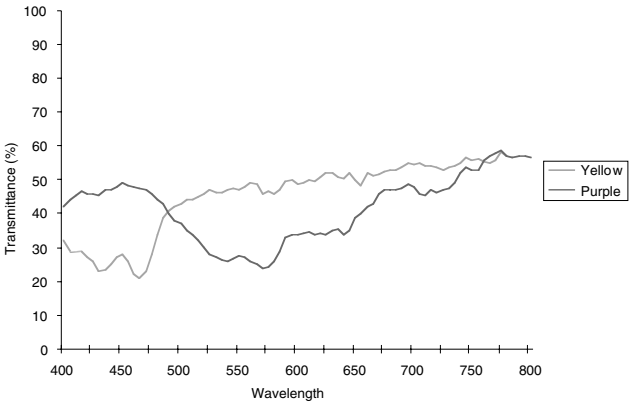

Fig. 1. Transmittance spectra of the yellow and purple Irlen transparencies.

2.2. Results and discussion

Total errors, time and comprehension scores were calculated from all seven passages read under the different transparencies and analyzed by paired, two-tailed *t*-tests. Alpha level was adjusted to 0.04 based on Bonferroni D/AP procedures that consider the number of comparisons and the correlation between measures (Sankoh, Huque, & Dubey, 1997). For this experiment, we have adequate power (0.80) to detect a population effect size of 0.60 or more. Effect sizes (Cohen's *d*) were calculated using Cohen's formula 2.3.9 (Cohen, 1988, p. 49), adjusting for the correlation between measures. Table 1 shows that participants performed significantly better on all reading measures with the shorter

Table 1
Means, *t*-test comparisons (two-tail), and 95% confidence interval for three reading measures under the yellow and purple transparencies

	Accuracy	Time (s)	Comprehension
Yellow	5.6	97.9	9.7
Purple	4.2	93.8	10.5
Difference	1.4	4.1	−0.8
t-value	3.87	5.44	−2.31
95% confidence interval	0.7–2.1	2.6–5.7	−1.5 to −0.1
p-value	0.0004	<0.0001	0.027
Cohen *d* effect size	0.90	1.24	0.69

wavelength transparency (purple). Overall, reading errors decreased 25%, time decreased 4%, and comprehension improved 8%. These results are consistent with previous studies that have used color transparencies, and show that reading using shorter wavelengths for reading improve performance.

3. Experiment 2: dichroic filters

Although these Irlen transparency data looked promising, the transmittance properties of the material acted more as a broad-band filter with a bias for shorter or longer wavelengths. Throughout most of the visible spectrum, transmittance rarely dropped below 25% for any wavelength with either color transparency. To more precisely examine the effects of shorter and longer wavelengths, a second experiment was conducted using high quality band-pass filters.

3.1. Method

3.1.1. Participants

Twenty-four college students from the Claremont Colleges in California volunteered to participate in this experiment. All had normal or correct-normal vision, and none had any history of reading or other learning disabilities. They also were screened for color blindness using the Ishihara's color deficiency test (1980), and none had read the passages used in the experiment.

3.1.2. Materials

Three Edmund Scientific additive dichroic color filters (set #J52-547) were used to filter a 75 W halogen light source. Each filter transmitted a specific range of short, medium, and long wavelengths, as measured by an Agilent 8453 UV–Visible spectrophotometer (see Fig. 2). Cone transmittance properties of the filters (see Table 2) were calculated using Stockman et al.'s tables of cone spectral sensitivity (Stockman & Sharpe, 2000; Stockman, Sharpe, & Fach, 1999) and the spectral transmittance of the filters. Four reading passages were taken from a Medical College Admissions Test (MCAT) preparation book. The first was a Scientific American article discussing sustainable agriculture, the second was an essay from Jung, the third was from a Sigma Xi publication on animal foraging strategies, and the fourth was an essay adapted from a book on cultural obligations of architects. Each passage had eight multiple-choice questions.

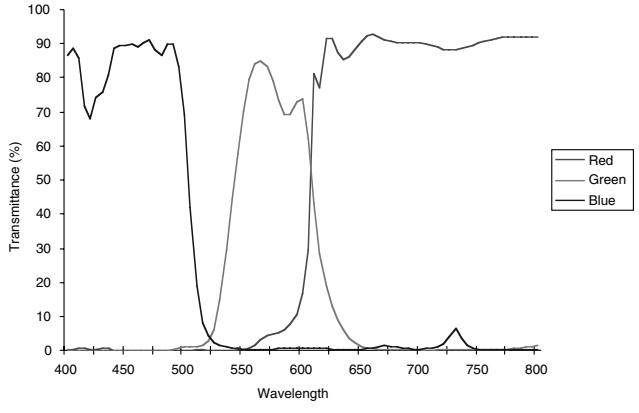

Fig. 2. Transmittance spectra of the red, green, and blue additive dichroic filters (Edmund Scientific set #J52-547).

Table 2
Transmittance of the Edmund Scientific dichroic filters for the three cones expressed as a percentage of normalized values

	Red	Green	Blue
Transmittance			
L-cone	19.08	45.56	8.09
M-cone	5.69	41.55	15.00
S-cone	0.17	0.18	83.33

3.1.3. Procedure

Participants read the four MCAT passages out loud with each passage displayed under a different color condition. Three color conditions were created using each dichroic filter (red, green, blue). A fourth, unfiltered condition also was included. Michelson contrast was 0.80 and luminance was adjusted to be 22 cd/m^2 in all conditions. Passage order and passage by color conditions were counterbalanced for the experiment. Participants were tested individually and instructed to read out loud as quickly as they could and told they would be timed for speed and checked for accuracy. They also were instructed to answer eight questions about each passage and told they would not be able to re-read the passage for reference while answering the questions. Participants were tape recorded, and total reading time and accuracy were scored blind from the tape using the GORT error scoring procedures.

3.2. Results and discussion

Reading time, accuracy, and comprehension for the four color conditions were examined in separate repeated-measures ANOVAs. In this experiment, we have adequate power (0.80) to detect a population effect size of 0.70 or more. There were no significant differences between color conditions for reading time ($F(3,69) = 0.74, p = 0.53$) or comprehension ($F(3,69) = 1.40,\ p = 25$), but accuracy was significantly affected by color ($F(3,69) = 4.12,\ p = 0.01$). Results are shown in Table 3. Red had the highest mean error rate (7.8), followed by green (6.5), blue (5.8), and unfiltered (5.4). Paired, two-tailed *t*-tests

Table 3
Mean and SE measures for reading time, accuracy, and comprehension in the four color conditions of experiment 2

	Accuracy		Time (s)		Comprehension	
	Mean	SE	Mean	SE	Mean	SE
Green	6.5	4.1	204.8	0.7	2.0	0.4
Blue	5.8	5.4	207.0	0.6	2.8	0.4
Red	7.8	3.9	205.9	0.7	2.9	0.4
Neutral	5.4	4.2	202.9	0.8	2.9	0.4

Table 4
t-test comparisons for reading accuracy in the four color conditions of experiment 2

	Mean difference	DF	*t*-value	*p*-value	95% confidence interval	Effect size (Cohen's *d*)
Blue–unfiltered	0.4	23	0.57	0.58	−1.1 to 1.9	0.17
Green–blue	0.6	23	1.00	0.38	−0.7 to 1.9	0.29
Green–unfiltered	1.0	23	1.27	0.22	−0.7 to 2.7	0.37
Red–green	1.3	23	2.17	0.04	−2.5 to −0.1	0.63
Red–blue	1.9	23	3.78	0.001	−3.0 to −0.9	1.10
Red–unfiltered	2.3	23	2.60	0.02	0.5 to 4.2	0.75

were conducted using a Bonferonni corrected alpha value of 0.02 based the D/AP procedure. *t*-tests showed participants made more reading errors with the red filter than in every other color condition, except green (see Table 4). There were no significant error differences between the green, blue, and unfiltered conditions.

These results are consistent with the first experiment. Color had its largest effect on accuracy in the first study, and accuracy was the only reading performance measure significantly affected in this second study. Instructions to participants in both experiments stressed speed without error, and results could change with different instructions.

Other studies have reported rate and comprehension to be the reading performance measures primarily affected by color, but in most cases such results can be explained by differences in procedures. For example, Iovino et al. (1998) found blue transparencies improved comprehension and rate, but not accuracy. In their study, rate and accuracy were measured together on a single word reading task (WRMT-R), and comprehension was measured on a second test, the Formal Reading Inventory. The WRMT-R instructions only stress accuracy and do not mention rate, so it is not too surprising that task difficulty was reflected in reading rate.

Reading errors increased with the addition of longer wavelengths of light, a pattern consistent with the hypothesis that activation of L-cones interferes with reading performance. The fact that there was no significant difference between the green and red filter conditions suggests that the band-pass characteristics of the green dichroic filter also provide sufficient energy for activation of the L-cones. The transmittance analysis of the filters (Table 2) support this interpretation, showing that more than half the light transmitted by the green filter activate the L-cones.

4. Experiment 3: too much red or not enough blue?

A third study was designed to replicate results of the second experiment and determine whether shorter wavelengths are improving reading performance or if longer wavelengths are interfering with text processing. Three different color conditions were constructed to test these two hypotheses. First, if shorter wavelengths improve reading, then a white light condition involving all three filters (B + G + R) will be better compared to a condition with green and red filters (G + R). In addition, performance with blue and green filters together (B + G) should be equal to the B + G + R condition. However, if longer wavelengths are interfering with reading, then performance in the B + G condition will be better than in the B + G + R condition. In addition, performance in the G + R condition will be equal to the B + G + R condition. Finally, if both hypotheses are correct, that is shorter wavelengths are improving reading performance and longer wavelengths are impairing it, then B + G performance will be better than B + G + R, but B + G + R performance also will be better than G + R. These three hypotheses are shown in Fig. 3.

4.1. Method

4.1.1. Participants

Eighteen college students from the Claremont Colleges in California volunteered for this study. They were screened for reading or other learning disabilities, color blindness, and had normal or corrected-normal visual

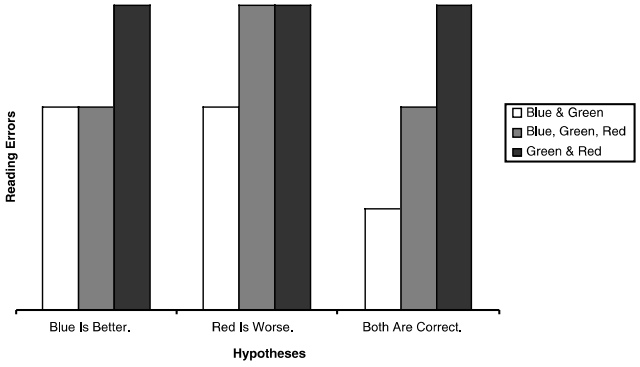

Fig. 3. Three hypothetical outcomes for experiment 3. Better performance is measured as a reduction in reading errors.

acuity. None had previously read the passages used in the experiment.

4.1.2. Materials

Three of MCAT passages used in experiment 2 (the sustainable agriculture passage was omitted) were used in this experiment. They were read under the three different lighting conditions described in Fig. 1 using two or three 75 W halogen lamps. In one condition the Edmund Scientific blue filter was combined with the green (B + G); in a second condition, all three filters were combined to produce a broad spectrum filter (B + G + R); in the third condition, the green filter was combined with the red (G + R). In the B + G + R condition, each filtered light source contributed 15 cd/m^2 of luminance (Fig. 3). In the G + R and B + G conditions, the green light source contributed 30 cd/m^2 and the blue and red light sources each contributed 15 cd/m^2, respectively. Total luminance was 45 cd/m^2 with an 80% Michelson contrast in each condition. Luminance through the red and blue filters were matched to be equal to 15 cd/m^2 in all three conditions to allow a direct comparison.

4.1.3. Procedures

Participants were tested individually. Each of the three passages was read under one of the three lighting conditions described above. Passage order and passage by color condition were counterbalanced for the experiment. The same instructions and scoring procedures used in experiment 2 were followed.

4.2. Results and discussion

Reading time, accuracy, and comprehension for the three color conditions were examined in separate repeated-measures ANOVAs. In this experiment, we have adequate power (0.80) to detect a population effect size of 0.80 or more. There were no differences between reading time ($F(2,34) = 1.17,\ p = 0.32$) and comprehension ($F(2,34) = 0.29,\ p = 0.75$), but accuracy was significantly affected by the different color conditions ($F(2,34) = 4.34,\ p = 0.02$). Results are presented in Table 5. The G + B + R color condition had the highest mean errors (6.2) followed by the R + G condition (5.7) and the G + B condition (4.4). One-tailed, paired *t*-tests were made with a Bonferroni alpha correction of 0.037, based on the D/AP procedure. Results supported the second hypothesis that longer wavelengths interfere with oral reading. Participants made significantly more reading errors in the B + G + R condition than the B + G condition and more errors in the G + R condition than the B + G, but G + R was not significantly different from B + G + R (see Table 6).

These results replicated experiment 2 and provide new evidence that longer wavelengths (red) impair reading performance. Reading accuracy was worse in the two color conditions that contained red light (B + G + R, G + R) and better in the condition without red (B + G). This finding is consistent with the physiological literature that shows red light suppresses functioning in the M pathway and suggests that M-cells make an important contribution to text perception.

Table 5
Mean and SE measures for reading time, accuracy, and comprehension in the three color conditions of experiment 3

	Accuracy		Time (s)		Comprehension	
	Mean	SE	Mean	SE	Mean	SE
G + B	4.4	0.7	193.8	5.8	2.7	0.5
G + B + R	6.2	0.9	196.6	5.3	3.1	0.4
R + G	5.7	0.8	197.8	5.6	2.7	0.4

Table 6
t-test comparisons for reading accuracy in the three color conditions of experiment 3

	Mean difference	DF	*t*-value	*p*-value	95% confidence interval	Effect size (Cohen's *d*)
G + B, G + B + R	−1.8	17	−2.56	0.01	−3.0 to −0.6	0.88
G + B, R + G	−1.3	17	−2.20	0.02	−2.3 to −0.3	0.74
R + G + B, R + G	0.5	17	0.86	0.80	−0.5 to 1.5	−0.29

5. Experiment 4: color and isoluminant text

Does red light disrupt both M- and P-cell function? Perhaps the red light conditions used in these three experiments provided insufficient information for normal visual discrimination, affecting P-cells too. If so, then the oral reading errors we found may not be solely the result of M-cell suppression but reflect a general reduction in letter and word perception.

This conclusion is unlikely, considering that reading performance has been found to be normal at luminance (Legge, Parish, Luebker, & Wurm, 1990) and contrast (Knoblauch, Arditi, & Szlyk, 1991) values well below those used in experiments 1–3. In addition, we do not know of any physiological evidence to suggest that parvocellular functioning can be suppressed by red light. In fact, Breitmeyer and Breier (1994) found that red light actually may enhance functioning in the P channel.

Such a result is consistent with a recent report on the chromatic-temporal receptive field properties of primary visual cortical (V1) neurons in Rhesus monkeys (Cottaris & De Valois, 1998). Some V1 neurons only responded to input from opponent L/M geniculate cells (single-peak), but other V1 neurons combined input from opponent L/M and S-cone geniculate cells (double-peak). Sluggish S-cone input delayed double-peaked cell response times by 20–60 ms compared to single-peak cells. Red light would suppress S-cone input, and so could act to speed up the processing of color information.

A fourth experiment was designed specifically to examine the effect of red light on P function in a reading task. In this experiment word pronunciation latencies were measured under isoluminant color conditions to examine the effect of red light on the P pathway. Isoluminant color displays have often been used as a condition for selectively measuring P function (Livingstone & Hubel, 1987), and Legge et al. (1990) reported color and luminance contrasts independently affected reading performance. Several studies (Knoblauch et al., 1991; Legge et al., 1990) have found that isoluminant color text can be read at normal rates. Even though the M pathway activity is difficult to silence with isoluminant stimuli (Lee, 1996), this experiment only needs a condition that is biased for P functioning and does not require eliminating M pathway activity.

5.1. Method

5.1.1. Participants

Twelve students from the Claremont Colleges in California volunteered for this study. All had normal or corrected-normal vision, none were color blind, and none had a history of reading or other learning disabilities.

5.1.2. Materials

A list of 60 high frequency, four to six letter words (mean = 245, range = 21–1303) were selected to be read out loud from the Kucera and Francis corpus (1967). Words were presented centered on a radius 17 inch color monitor using a Macintosh 7100 and SuperLab Pro software. Pixel resolution was set to 1024 by 768 at 75 Hz raster rate and a viewing distance of 20 cm. At this distance, six letter words subtended a viewing angle of about 6 deg. Words were presented in Monaco, 20 point uppercase font in an isoluminant 28 cd/m^2 display with green text centered on a red background. Participants viewed the text either through clear or the dichroic red filters described in experiment 2.

Luminance measurements were taken through the filters using a Minolta LS-100 photometer. 3.3% of the irradiance from the green phosphor was transmitted through the red filter due to spectral overlap. The intensity of the red background was reduced to equal the maximum luminance of the green text. To increase overall luminance of the display, an external halogen spot light was projected onto the CRT screen to achieve 28 cd/m^2. Equalizing luminance by photometer measurement has been shown to produce isoluminant values that are similar to those found with flicker photometry (Pammer & Lovegrove, submitted for publication).

5.1.3. Procedure

Each trial began with a fixation point "+" centered on the screen. After a key press, a 250 ms tone was presented, followed by a 250 ms premask "######" and then one of the 60 target words. Participants were instructed to read the word out loud as quickly as they could without making a mistake. Vocal latencies were recorded by microphone and SuperLab Pro software. The 60 words were divided into two lists of 30 words that were matched for word frequency, number of letters, phonemes, and syllables. Participants saw one word list with red filters and the other list with clear, and word order was random for each subject in each block. Color conditions were blocked and counterbalanced for order of the color blocks and for word list by color condition throughout the experiment.

5.2. Results and discussion

Trial data was trimmed for responses below 250 ms and above 1000 ms. The lower threshold of 250 ms eliminated false vocalization responses (e.g., clearing the throat) and only affected 11 trials. The upper threshold was somewhat arbitrary and represented about a 1 1/2 SD cut-off above the untrimmed mean of 741 ms. One trial was omitted for a mispronounced word. In total, 3.6% of the trials were omitted. Results for the two color conditions were analyzed in a two-tailed, paired *t*-test.

In this experiment, we have adequate power (0.80) to detect a population effect size of 1.0 or more.

Participants responded faster ($t(11) = 3.57$, $p = 0.004$) in the red color condition (485.4 ms) than in the clear condition (507.0 ms). The mean difference between the color conditions was 21.6 ms with a 95% confidence interval from 8.3 to 34.9. The effect size (Cohen's d) was 1.52, based the adjusted formula for correlation between the means.

These results show that under isoluminant conditions, single word reading speed improves with a red background. Since text perception with isoluminant displays depends upon color contrast and therefore is more dependent upon the P neurons that respond to color, these findings suggest that P-cell function may improve with longer wavelengths. However, results from experiments 1–3 showed that under normal luminance contrast, performance was impaired by red light. These discrepant results suggest that the M system provides the dominant source of information for text perception under normal contrast conditions.

6. General discussion

Together these four experiments support the conclusion that oral reading performance among fluent adult readers is better when longer wavelengths (red) are removed from the light source. Other studies have proposed that shorter wavelengths (blue) may actually enhance reading performance, particularly for impaired younger readers (Solan, 1998; Williams et al., 1992). However, these studies were not designed to determine whether it was absence of red or the presence of blue light that caused the improvement. Both blue or neutral gray density filters would have the effect of reducing the contribution of longer wavelengths in text illumination. Our third experiment showed that the longer wavelengths (red) interfered with text processing and suggest that enhanced reading performance with blue or gray filters is due to their reduction of red light.

Our fourth experiment showed that the impairment of reading under red light in experiments 1–3 was due to a suppression of M pathway function. Single word reading was faster with red light under conditions that more selectively activate the P pathway. The combinations of these experiments, together with the evidence from the physiological literature, suggests that the M pathway is the major visual system for text processing under normal luminance contrast conditions.

Several questions remain for further study. What stages of text processing are most disrupted by red light? Few studies have examined color and reading, and we know of none that have looked at stages of text processing and color. The Chase (1996) and Breitmeyer (1980) reading models describe different functional roles for the M channel in reading and so make different predictions about how red light will affect text perception.

In the Chase model, red light will impair the processing of the low SFs of text contained in the M channel and hamper the analysis of orthography dependent on global pattern information. Finer visual details, processed in the P pathway, should not be affected by the red light. In contrast, the Breitmeyer model predicts that because of red suppression, the M pathway will be slow to inhibit the P channel, causing a build-up of multiple saccadic images in the P channel. Since Breitmeyer's model presumes that all text processing occurs in the P or sustained channel, both global patterns as well as fine visual details should be disrupted by red light.

A further difference between the two models concerns the temporal course of the red light effects. The Chase model predicts that red light will disrupt orthographic processing at the pre-lexical stage, affecting the perception of letter and word shape. Since the M channel is faster than the P channel, finer visual details added by the P pathway may be used to resolve ambiguity at later, post-lexical stages. Because P channel information has not been impaired by red light, but may in fact be enhanced by it, such additional details may be processed more rapidly under red light and enhance lexical access. The Breitmeyer model predicts that all SF aspects of text are equally impaired by red light and will affect both orthographic and lexical stages of text processing.

The results of these studies also have implications for dyslexic research. If some dyslexic children suffer from M channel processing impairments, additional color research may help identify the stages of text processing affected by the dyslexic magnocellular deficits. The Chase model, for example, suggests orthography may be an important area for further dyslexic research.

Dyslexics may show different patterns of results depending upon their reading strategy. Some dyslexic readers with M impairments may learn to depend upon their P pathway for text processing. Slowing down while reading may provide them an opportunity to gather more information from the slower P pathway, making text easier to process. Such slower dyslexic readers may actually be less susceptible to the effects of red light on text since they are not using their M pathway as much as normal readers. Faster dyslexic readers, however, may continue to depend on their M pathway and therefore could be more susceptible to red light disruption. Little is understood about the relative contributions of the P and M channels for text processing and how information is integrated between them. Problems in the strategic allocation of attention between the channels could be a more general source of reading difficulty, particularly when one pathway has defects.

Finally, future experiments designed to study dyslexia, color, and reading may benefit from the use of

high quality filters or other monitor calibration procedures that can control precisely the wavelengths of light. Experimental procedures also should be explicit about the reading instructions given and what task (speed, accuracy, comprehension) was most important. Such technical improvements may produce more consistent results.

Acknowledgements

The study was supported in part by a grant from the National Institute of Neurological Disorders and Stroke (R29-NS34029). The authors thank Bob Dougherty, Brian Wandell, and two anonymous reviews for their helpful comments.

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